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DESIGN PARAMETERS AND PERFORMANCE CHARACTERISTICS OF A MINIATURE PRESSURE-TRANSDUCER SYSTEM USING A FLUID-FILLED BELLOWS SENSOR

by

John R. Folkrod

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Reactor Engineering Division

October 1969

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NOMENCLATURE

[illegible]

[illegible] Pressure-
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[illegible] Rate of
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Schematic of [illegible]

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Table

[illegible] Stem Bellows [illegible]

[illegible] Stem Bellows [illegible]

NOMENCLATURE

Symbol	Description
A_b	Effective area of bellows, in.^{2}
A_t	Area of transducer diaphragm, in.^{2}
D_t	Diameter of transducer diaphragm, in.
E_0	Initial value of Young's modulus, psi
E_1	Young's modulus at operating temperature, psi
F	Force acting outside bellows, lb
F_1	Force acting inside bellows due to fluid expansion, lb
F_2	Force acting inside bellows due to spring rate of bellows, lb
F_3	Force acting on transducer diaphragm, lb
h	Height of spherical segment formed by diaphragm deflection, in.
K_{b0}	Initial spring rate of bellows, lb/in.
K_{b1}	Bellows spring rate at operating temperature, lb/in.
K_t	Spring rate of transducer, lb/in.
P	System pressure to be measured, psig
P_0	Initial pressure of fluid in transducer system, psig
P_1	Operating pressure of fluid in transducer system, psig
p_0	Absolute pressure at initial conditions, psia
p_1	Absolute pressure at condition 1, psia
S	Actual bellows stroke, in.
S_c	Compression stroke of bellows, in.
S'_c	Total compression stroke caused by outside pressure and change in void volume, in.
S_e	Bellows stroke due to fluid expansion, in.
T_0	Initial temperature of void volume, °R
T_1	Operating temperature of void volume, °R
ΔT	Temperature change in transducer system, °F
V	Volume created by transducer diaphragm deflection, in.^{3}
V_f	Initial volume of coupling fluid, in.^{3}
V_0	Initial volume of transducer system, in.^{3}
V_{v0}	Initial void volume in transducer fluid, in.^{3}
V_{v1}	Operating void volume in transducer fluid, in.^{3}
ΔV_b	Volume change in bellows due to total stroke of bellows, in.^{3}
ΔV_{b1}	Volume change due to thermal expansion of bellows metal, in.^{3}
$\Delta V'_b$	Volume change in bellows due to fluid expansion, in.^{3}
ΔV_t	Volume change in transducer due to fluid pressure, in.^{3}
ΔV_{bt}	Volume change in bellows due to pressure in bellows, in.^{3}
ΔV_{bv}	Volume change in bellows due to void volume change, in.^{3}
ΔV_f	Gross change in fluid volume due to temperature, in.^{3}
$\Delta V'_f$	Net change in fluid volume due to temperature, in.^{3}
β_f	Coefficient of fluid volume change, °F^{-1}
β_m	Coefficient of linear expansion of metal in transducer system, °F^{-1}

DESIGN PARAMETERS AND PERFORMANCE CHARACTERISTICS OF A MINIATURE PRESSURE-TRANSDUCER SYSTEM USING A FLUID-FILLED BELLOWS SENSOR

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ABSTRACT

Optimal design parameters are developed and two working models are assembled to demonstrate the feasibility of transmitting fission-gas pressures generated in LMFBR-type fuel pins via a miniature, NaK-filled bellows-capillary tube to a strain-gauge transducer located outside the core environment. The key problem is obtaining a voidless fill.

Both models were readily assembled, using commercially available components. The first model featured a 5/8-in.-OD stainless steel bellows welded to a 1/8-in.-OD, 1/16-in.-ID stainless steel capillary tube, 24 ft long, which, in turn, was welded to a strain-gauge transducer. After filling with NaK, the transducer system was calibrated and then operated continuously for three months at 1200°F. During this period, the "sensing" end of the bellows was exposed to 120 pressure cycles (0-100 psig) without malfunction. Comparison of transducer outputs with precision-gauge readouts on the pressurizing chamber indicated a system accuracy of ±1/3% and a time response of 1 sec.

The second model was an attempt toward the ideal system. For immediate purposes, a nickel bellows of 1/8-in. OD was procured and similarly interconnected with a 0.020-in.-ID stainless steel capillary tube. Several cleaning and filling procedures were required before the slightest compression of the bellows resulted in essentially full deflection of the transducer diaphragm, indicative of a voidless fill. Bellows failure due to nickel embrittlement precluded system calibration.

It is concluded that, with improvements in filling techniques, a commercially available stainless steel bellows of 0.220-in. OD coupled to a capillary tube of 0.012-in. ID would satisfy criteria established for LMFBR fission-gas pressure sensors.

I. INTRODUCTION

Development of competitive Liquid Metal Fast Breeder Reactor (LMFBR) central-station power plants depends upon the availability of cladding fuel elements that can be operated at the highest specific power level with safety and without shortening of service lifetime. In the interests of economics, these elements should have the lowest cladding metal-to-fuel ratio consistent with effectively isolating the fuel and attendant fission products from the reactor coolant. Availability of such fuel elements, in turn, depends upon the development of in-core instruments that will provide data needed to resolve design problems that affect their behavior and service lifetime.

One particularly pressing problem faced by LMFBR fuel-element designers, and one for which insufficient data exist, is to determine the relationship between fuel burnup, generation of fission gases, and fuel-swelling behavior. The target burnup of LMFBR fuels (100,000 MWd/T) will result in significant generation of fission gases, atoms of which migrate through the fuel and collect in the fuel element under very high pressure. It is estimated that pressures up to 1000 psi may be reached. If the fuel element is to retain its integrity, the cladding must retain the fuel without exceeding the cladding strength and/or ductility limit. Thus it is highly desirable to have the capability of continuously monitoring internal pressures of candidate fuel elements during experimental irradiation in facilities designed to simulate the anticipated LMFBR operating environments--e.g., the Fast Flux Test Facility (FFTF) or the Experimental Breeder Reactor-II (EBR-II).

Interest in the development of reliable fuel-pressure sensors is not limited to these experimental irradiations. With sufficient knowledge of the pressure-buildup phenomena in candidate fuel elements, extrapolation to LMFBR core environments may be sufficient. However, if not too difficult and expensive, installation of similar sensors on fuel elements in the LMFBRs also may yield information vital to plant safety, at least in the early stages of operation. For example, fission-gas pressure might be a good indicator of leaking fuel cladding, the first and fastest indication of fuel failure, and possibly a means of inferring fuel melting.

Accordingly, considerable effort is being expended at Argonne: (1) to evaluate commercially supplied, miniature pressure-transducer systems, or parts thereof, which have potential application for monitoring fission-gas pressures in LMFBR-type fuel elements; and (2) to modify, improve, develop, assemble, and conduct out-of-pile tests on integrated systems to the point where proof-of-principle has been successfully demonstrated. Thereafter, industrial participation will be contracted to supply prototype systems for comprehensive evaluation in the FFTF or the EBR-II.

Specifically sought are pressure sensors that meet the following criteria:

Environmental Conditions

Reactor coolant	Sodium
Sodium temperature	$\leq$1400°F
Fast-neutron flux	10^{16} nv
Integrated fast-neutron flux	10^{23} nvt
Gamma flux	$\leq 10^9$ R/hr

Functional Requirements and Constraints

Range	0-1000 psi
Drift	<0.1% full scale/week
Response time	<1 sec
Diameter	0.25-0.625 in.

This report describes the design parameters and results of out-of-pile tests on a pressure-sensing system that holds promise in meeting these criteria.

II. PRINCIPLE OF OPERATION AND DESIGN PARAMETERS

A. Principle of Operation

The system design is based upon the capillary tube-diaphragm principle of operation, with one significant modification. Commercial systems based upon this principle use diaphragms that are too large and do not have the short response times required for the proposed application. Therefore, the modification consists of using a metal bellows and a capillary tube, filled with an incompressible fluid. The diameter of the bellows can be less than the ID of most fuel cladding, and the fluid can be NaK.

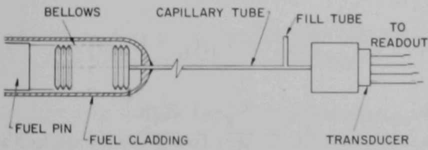

Fig. 1. Schematic Assembly of Miniature Fission-gas Pressure-sensing System Using a Bellows-capillary tube

As shown in Fig. 1, the bellows and one end of the capillary tube are sealed to an experimental fuel element positioned in the reactor core. The other end of the tube is sealed to the diaphragm of a strain-gauge pressure transducer located outside the hostile environment. In operation, the fission-gas pressure impinges upon the bellows. Compression of the bellows forces the fluid against the diaphragm, which deflects according to the pressure applied.

B. Design Parameters

1. Transducer Volume Change

The diaphragm deflects linearly, and the volume of the spherical displacement is given by

$$V = \tfrac{1}{6}\pi h\left(\tfrac{3}{4}D_t^2 + h^2\right). \tag{1}$$

Generally, h is a very small number; therefore h^3 can be eliminated. Thus, the volume required by the bellows compression to yield a pressure reading is

$$V = \frac{\pi}{8}hD_t^2$$

$$= \frac{A_t h}{2}. \tag{2}$$

2. Bellows Compression Stroke

The volume supplied by the bellows and equal to Eq. 2 is given by

$$V = A_b S_c. \tag{3}$$

Thus the bellows compression stroke is

$$S_c = \frac{1}{2}\frac{A_t}{A_b}h. \tag{4}$$

3. Bellows Spring Rate

The spring rate of the bellows must be considered because it will resist compression of the bellows. For example, in Fig. 2,

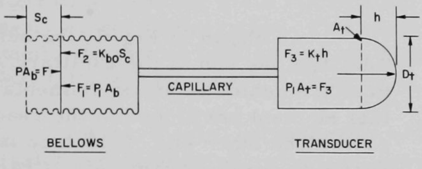

Fig. 2. Force Balance Showing Effect of Bellows Spring Rate on System under Pressure P

$$F = F_1 + F_2, \tag{5}$$

$$PA_b = P_1A_b + K_{b0}S_c, \tag{6}$$

$$P_1 = \frac{F_3}{A_t} = \frac{K_t h}{A_t}, \tag{7}$$

and

$$P = \frac{K_t h}{A_t} + \frac{K_{b0}S_c}{A_b}. \tag{8}$$

On solving for h in Eq. 4 and substituting in Eq. 8, we obtain

$$P = \frac{K_t}{A_t}\frac{2A_bS_c}{A_t} + \frac{K_{b0}S_c}{A_b},$$

which yields

$$S_c = \frac{P}{2K_t A_b/A_t^2 + K_{b0}/A_b}. \tag{9}$$

The term K_{b0}/A_b in Eq. 9 will affect bellows displacement and cause the transducer to sense less than the applied pressure. This is not a problem, since the system can be calibrated; however, the value must be kept low enough so that as much as possible of the transducer deflection is used for sensing purposes. For constant system temperature, the denominator is a constant. Therefore

$$S_c = \frac{P}{C}, \tag{10}$$

and the actual system pressure the transducer will sense is

$$P_1 = P - \frac{K_{b0}S_c}{A_b}. \tag{11}$$

4. Void Effect

If the system is not filled completely, further bellows displacement will be required to overcome the void effect.

The void volume changes according to

$$V_{v1} = V_{v0}\frac{p_0 T_1}{p_1 T_0}, \tag{12}$$

where p_0 and p_1 are absolute pressures. At constant system temperature, the temperature ratio is unity.

The total compression stroke caused by outside pressure and change in void volume is computed as follows: From the force balance (Fig. 3), one can equate

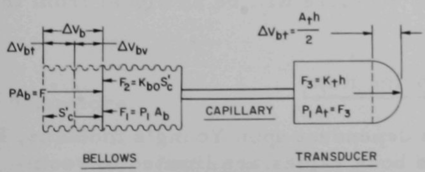

Fig. 3. Force Balance of System Containing Voids

$$\Delta V_b = \Delta V_{bt} + \Delta V_{bv}, \tag{13}$$

which is the volume change of transducer and void.

The total stroke of the bellows is

$$S_c' = S_c + \frac{\Delta V_{bv}}{A_b}, \tag{14}$$

where

$$\Delta V_{bv} = V_{v0} - V_{v1}. \tag{15}$$

Substituting Eq. 12 for V_{v1} in Eq. 15 gives

$$\Delta V_{bv} = V_{v0}\left(1 - \frac{p_0 T_1}{p_1 T_0}\right). \tag{16}$$

Therefore

$$S_c' = S_c + \frac{V_{v0}}{A_b}\left(1 - \frac{p_0 T_1}{p_1 T_0}\right). \tag{17}$$

Next, substituting the absolute value of P_1 given by Eq. 11 results in

$$S_c' = S_c + \frac{V_{v0}}{A_b}\left[1 - \frac{p_0 T_1}{(P - K_{b0} S_c/A_b + 15)\, T_0}\right]. \tag{18}$$

Finally, substituting P/C for S_c from Eq. 10 gives

$$S_c' = \frac{P}{C} + \frac{V_{v0}}{A_b}\left[1 - \frac{p_0 T_1}{\{P(1 - K_{b0}/CA_b) + 15\}\, T_0}\right]. \tag{19}$$

A voidless fill gives a linear relationship of pressure to bellows displacement. A system having voids will cause a deviation from this linearity, as affected by the second term in Eq. 19. This deviation will not affect system operation since nonlinear curves can be used, provided they are reproducible. On the other hand, difficulties may be encountered if S_c' becomes too large. For example, the coupling fluid pressure is

$$P_1 = P - \frac{K_{b0} S_c'}{A_b}. \tag{20}$$

If the second term in Eq. 20 is equal to P, there will be no signal from the transducer.

5. Temperature Effects on Spring Rate

The bellows spring rate is dependent upon Young's modulus, E, of the material employed. Spring-rate book values are limited to room-temperature conditions; however, moduli of elasticity are available for ferrous materials at temperatures up to 1400°F. Therefore, the corresponding spring rates can be determined simply by multiplying K_b by E_1/E_0.

Accordingly, equations containing K_{b0} can be corrected for temperature effects by replacing K_{b0} with K_{b1}, where

$$K_{b1} = K_{b0}E_1/E_0. \tag{21}$$

6. Expansion Effects without Voids

As the system temperature increases, the coupling fluid expands according to the coefficient of volume expansion rate, and the bellows according to the coefficient of linear expansion rate for the metal. Therefore the volume changes in the fluid and in the metal expansion are:

$$\Delta V_f = V_f \beta_f \Delta T \qquad \text{(fluid)} \tag{22}$$

and

$$\Delta V_{b1} = V_0[(1 + \beta_m \Delta T)^3 - 1] \qquad \text{(bellows + part of capillary)}, \tag{23}$$

where $V_f = V_0$ if there are no voids. The difference between ΔV_f and ΔV_{b1} will be the net volume change ($\Delta V_f'$) in the bellows and transducer diaphragm to accommodate the fluid. This will affect the pressure P_1 of the fluid due to the spring rates.

For example, let K_{b1} represent the spring rate for the bellows temperature compensation in a system at T_1 with an expansion stroke S_e, as shown in Fig. 4. Here, the net change in fluid volume ($\Delta V_f'$) causes the pressure buildup and is

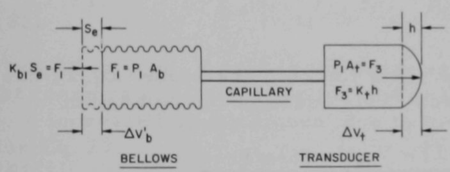

Fig. 4. Force Balance of System at Temperature T_1, with an Expansion Stroke S_e, and No Voids

$$\Delta V_f' = \Delta V_b' + \Delta V_t, \tag{24}$$

where

$$\Delta V_b' = S_e A_b$$

and

$$\Delta V_t = \frac{A_t h}{2}.$$

Therefore,

$$\Delta V_f' = S_e A_b + \frac{A_t h}{2}. \tag{25}$$

But, as stated earlier,

$$\Delta V_f' = \Delta V_f - \Delta V_{b1}.$$

Hence, on replacing ΔV_f and ΔV_{b1} with Eqs. 22 and 23, respectively, and using V_0 for the initial system volume to be heated, we obtain

$$\Delta V_f' = V_0[\beta_f \Delta T - (1 + \beta_m \Delta T)^3 + 1]. \tag{26}$$

Finally, on substituting Eq. 25 for $\Delta V_f'$, replacing S_e and h with $P_1(A_b/K_{b1})$ and $P_1(A_t/K_t)$, respectively, and solving for P_1, we obtain

$$P_1 = V_0 \frac{\beta_f \Delta T - (1 + \beta_m \Delta T)^3 + 1}{A_b^2/K_{b1} + A_t^2/2K_t}. \tag{27}$$

Examination of Eq. 27 reveals that V_0 and A_b^2/K_{b1} are the determining parameters for a high or low value of P_1, and that a high value can be readily achieved with a large heated volume. In a system design, this is the first parameter that should be examined in detail.

7. Expansion Effects with Voids

If voids are present in the coupling fluid, the void volume may either expand along with the fluid or decrease, depending upon the temperature-pressure relationship.

The void volume change is given by Eq. 12, and the net volume change by

$$\Delta V_f' = \Delta V_f - \Delta V_{b1} - \Delta V_{bv}, \tag{28}$$

where the first two right-hand terms equal Eq. 26. Therefore, Eq. 27 has an added term: the void volume effect. This equation can be written

$$P_1 = \frac{V_0[\beta_f \Delta T - (1 + \beta_m \Delta T)^3 + 1] - V_{v0}(1 - p_0 T_1/p_1 T_0)}{A_b^2/K_{b1} + A_t^2/2K_t}. \tag{29}$$

Equation 29 is applicable only if all the void volume "sees" the system temperature. If such is not the case, V_{v0} or T_1 must be proportioned to account for any temperature gradient.

8. Bellows under Pressure at Temperature without Voids

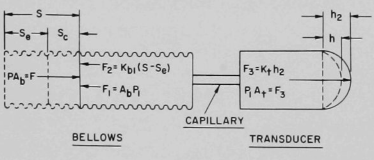

Fig. 5. Force Balance of Voidless System, with Bellows in Compressed State

As shown in Fig. 5, with the system at temperature and with external pressure applied at the bellows, the force from the bellows reaction decreases from the tension condition, increases upon bellows compression, and has an opposite sign; that is,

$$F_2 = K_{b1}(S - S_e).$$

Therefore, the force balance is

$$PA_b = P_1A_b + K_{b1}(S - S_e). \tag{30}$$

The volume changes also have to balance; that is,

$$S_eA_b = \frac{A_t(h_2 - h)}{2} \tag{31}$$

and

$$S_eA_b = V_0[\beta_f\Delta T - (1 + \beta_m\Delta T)^3 + 1] - A_th/2. \tag{32}$$

Hence,

$$PA_b = P_1A_b + K_{b1}\left\{\frac{A_t/A_b}{2}(h_2 - h)\ \frac{V_0}{A_b}[\beta_f\Delta T - (1 + \beta_m\Delta T)^3 + 1] + \frac{A_t/A_b}{2}h\right\}. \tag{33}$$

On simplifying Eq. 33 and replacing h_2 with P_1A_t/K_t, we get

$$P_1 = \frac{P + V_0(K_{b1}/A_b^2)[\beta_f\Delta T - (1 + \beta_m\Delta T)^3 + 1]}{1 + [(A_t/A_b)^2(K_{b1}/K_t)/2]}. \tag{34}$$

When ΔT is zero, Eq. 34 is the same as Eq. 11 with S_c replaced by Eq. 9. The temperature-effect portion of Eq. 29 is equal to Eq. 27. Therefore, P_1 is increased by the amount due to the expansion effect, or Eq. 11 plus Eq. 27.

9. Bellows under Pressure at Temperature and with Voids in the System

With the bellows under pressure at temperature and with voids in the system, the pressure (P_1) inside the bellows is equal to the sum of Eqs. 20 and 27, with Eq. 19 substituted for S_c'. Literally, this means that the inside pressure is equal to the outside pressure, plus or minus the void effect, plus the expansion effect. At low pressures, the void effect (because it has a positive value) compounds the expansion effect. As the pressure increases, the void effect becomes negative and has less influence on the expansion effect.

III. PERFORMANCE CHARACTERISTICS

Two, NaK-filled, bellows-capillary transducer systems--one with a 5/8-in.-diam bellows and the other with a 1/8-in.-diam bellows--were assembled for out-of-pile tests at temperatures up to 1200°F. Commercially-available components were used in each system. This section describes the mode of assembly and the subsequent experience with each system.

A. 5/8-in.-diam Bellows System

Table I lists the pertinent design data for this system.

TABLE I. Design Data for 5/8-in.-diam Bellows System

Bellows[a]	
Convolutions	Nesting-ripple
Material	AM-350 SS
Inside diameter	0.320 in.
Outside diameter	0.620 in.
Free length	1.0 in.
Effective area	0.173 in.^{2}
Spring rate	1.825 lb/in.
Pressure Transducer	
Type	CEC 4-317 strain gauge
Pressure rating	0-300 psig (21.2 mV at 300 psig)
Temperature rating	600°F
Effective diaphragm diameter	0.5 in.
Deflection at rated pressure	0.0008 in.
Capillary Tube	
Material	Type 304 SS
Length	24 ft
Inside diameter	0.0625 in.
Outside diameter	0.125 in.

[a]Product of Metal Bellows Corp., Sharon, Mass.

1. System Assembly and Calibration

With reference to Fig. 6, the sequence of system assembly and calibration for test purposes was as follows:

a. Clean the capillary tube and the bellows with acetone; purge the excess with argon.

b. Weld the capillary tube to the bellows, the fill tube, and the transducer.

c. Attach the dual-valved fitting leading from the vacuum source and NaK reservoir to the fill tube at the transducer end.

d. Open the valve from the vacuum source; heat the system to 200°F, and evacuate for 24 hr. (Note: The bellows end was evacuated to 1 μHg.) Cool the system to room temperature. Close the valve from the vacuum source.

e. Open the valve from the NaK reservoir and the fill system; pressurize the reservoir sufficiently to cause slight longitudinal expansion of the bellows.

f. Pinch the fill tube; close the valve from the NaK reservoir; sever the NaK supply line; clean and seal-weld the pinched end of the fill tube.

g. Connect the transducer input to a constant 5-V dc supply, and the transducer output to a potentiometer. Calibrate the system at room temperature, using a 0- to 150-psi precision gauge graduated in 1/4-psi increments. The results are shown in Fig. 7.

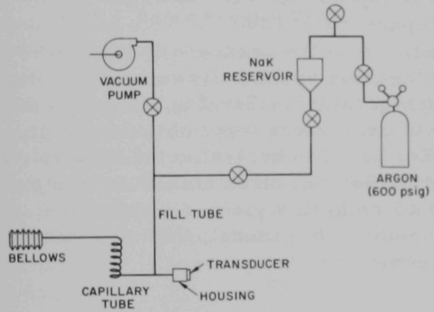

Fig. 6. Schematic of Test Assembly of 5/8-in.-diam Bellows System

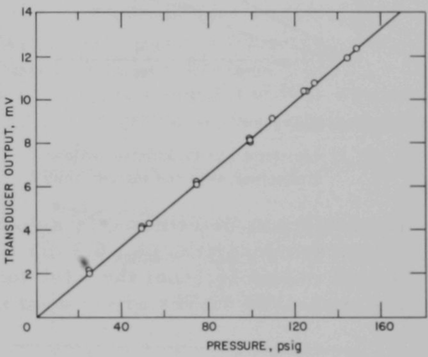

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Fig. 7. Calibration of 5/8-in.-diam Bellows System at Room Temperature

2. <u>Test Procedures and Results</u>

Initially, comparison plots were made of measured and calculated values of bellows deflection versus pressure for the system with and without voids at room temperature. Measured values were obtained by: (1) applying a series of bellows compression strokes with a micrometer and plotting the corresponding transducer outputs (in mV), and (2) using the calibration curve to convert these outputs into psig. A void volume of 0.01855 in.^{3} at zero psig was calculated using Eq. 19.

As shown in Fig. 8, there is excellent agreement between measured and calculated values at system pressures above 70 psig. The

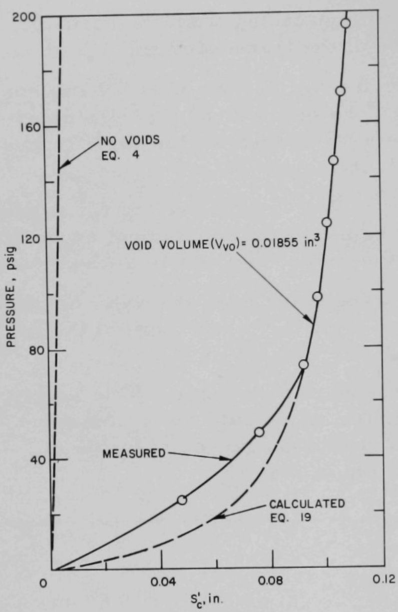

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Fig. 8. Measured and Calculated Bellows Deflection, with and without Voids

reason for disagreement at lower pressures is subject to further investigation. According to Eq. 19, the void effect should be more significant at lower pressures because it changes at a faster rate. Measurement of the force to cause bellows deflection might shed some light on the reason for disagreement. However, such measurements were not made, in view of the excellent agreement at the higher pressures.

Next, clamshell heaters were installed around the bellows, and strip heaters were wrapped around 8 ft of the adjoining capillary tube. The objective here was to determine the effect of temperature on system performance. As evidenced by Fig. 9, the pressure buildup due to voids and NaK expansion tapers off at 1200°F. This is attributed mainly to the decrease in modulus of elasticity of the bellows metal at that temperature. (See Fig. 10.) The calculated curves were obtained using Eq. 29. The heat-affected void volume at 1200°F was determined by substituting the measured transducer output at that temperature, i.e., 0.3 mV or 3.65 psig; this yielded a value of 0.0105 in.^{3} or 56.5% of the total void volume. In general, the calculated and measured curves are in good agreement.

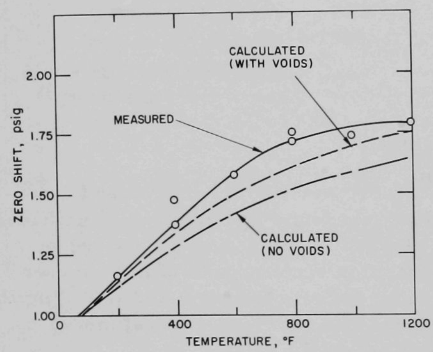

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Fig. 9. Effect of Temperature on Zero Shift of 5/8-in.-diam Bellows System

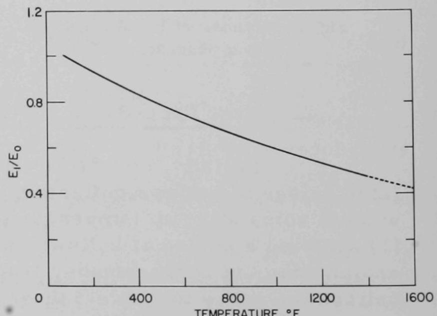

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Fig. 10. Effect of Temperature on Modulus of Elasticity of AM-350 Stainless Steel

The system was then operated continuously for three months without failure. During this period, the bellows was heated to a constant value of 1200°F and, at specified intervals, pressure-cycled from zero to 100 psig. About 120 cycles were completed during the test.

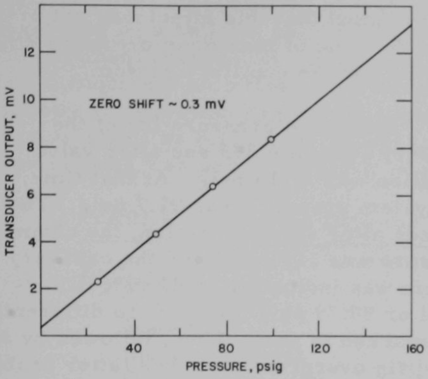

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Fig. 11. Calibration of 5/8-in.-diam Bellows System at 1200°F

Transducer outputs were recorded on a 0- to 10-mV Honeywell recorder having a sensitivity of ±0.5 psig. Unfortunately, the constant-voltage supply was prone to minor fluctuations. As a consequence, the spread in transducer output was 8.00 to 8.8 mV (97.2 to 106.8 psig). The average output for the three-month period was 8.246 mV, which is equal to the calibration of 8.24 mV for 100 psig. (See Fig. 11.)

The final test was designed to measure system time response. Two techniques were employed. First, the bellows end was connected to a chamber equipped with a strain-gauge pressure transducer similar to the one installed on the capillary tube. This chamber was supplied with 100-psig gas controlled by two manually operated ball valves, one at the inlet and one at the outlet of the chamber. Both transducers were readout on a Honeywell "Electronik 19" two-pen recorder. Chart speed was set at 1 in./sec.

In operation, the chamber was pressurized or depressurized by opening and closing the appropriate valves. Figure 12 shows the time response of the strain-gauge pressure transducer and the bellows system upon being pressurized and depressurized.

In the second technique, the time response was determined by electrically connecting both transducers to give the difference in millivolts and then calculating the difference in pressure, using the conversion factor 0.025 psig/mV.

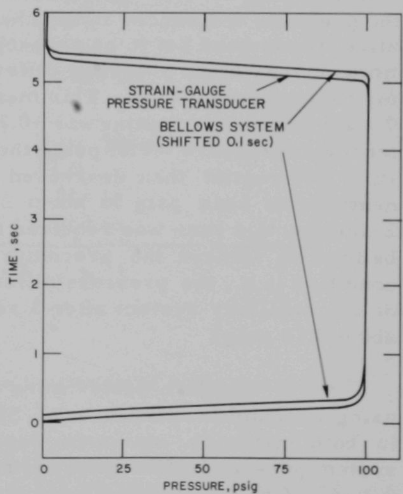

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Fig. 12. Time Response of Bellows System upon Pressurization of Chamber from Zero to 100 psig

Figure 13 shows the pressure differential of the capillary system generated upon pressurizing the chamber. The positive spike represents the pressure differential in overcoming the inertia of the diaphragm of the pressure transducer in the chamber. It is assumed that this effect was not present at the time of maximum pressure differential for the capillary system.

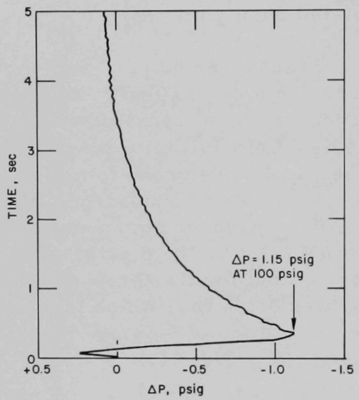

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Fig. 13. Pressure Differential of Bellows System upon Pressurization of Chamber from Zero to 100 psig

Maximum pressure lag of the capillary system 0.375 sec after valve operation was -1.15 psig. At that time, the system pressure was 97.7 psig. Two seconds after valve operation, the chamber pressure was 100 psig, and the capillary system was indicating -0.21 psig differential or 99.79 psig total. Zero differential was reached in about 4 sec, followed by a +0.1-psig overpressure. The latter probably was due to inertial effects of the bellows. Eighteen seconds elapsed before the system stabilized at zero differential.

Figure 14 shows the corresponding pressure differential of the capillary system upon depressurizing the chamber. Inertial effects of the diaphragm of the pressure transducer in the chamber are again evident and, again, this effect is assumed not to be present at the time of maximum pressure differential for the capillary system. This maximum 0.3 sec after valve opening was +0.25 psig (chamber pressure = 0.05 psig); the pressure differential then decreased exponentially to zero psig in about 20 sec. Evidently, this time was required for the bellows to achieve the precompression condition (e.g., the pressure differential of the capillary system after 3 sec was about 0.12 psig).

Similar tests were made using a chamber pressure of 50 psig. In both instances, maximum capillary-system pressure differential was reached 0.3 sec after valve operation: -0.7 psig upon pressurization, and +0.275 psig upon depressurization of the chamber.

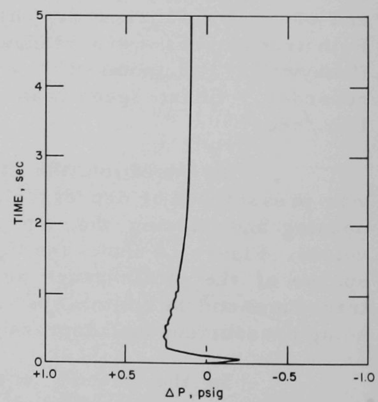

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Fig. 14. Pressure Differential of Bellows System upon Depressurization of Chamber from 100 to Zero psig

B. 1/8-in.-diam Bellows System

The primary objective was to demonstrate the workability of an idealized pressure-sensing system whose pressure signals would be generated by a bellows sealed inside the fuel-pin cladding. Table II lists the pertinent design data. A system designed for operation at 1200°F would require a stainless steel, nesting-ripple type bellows. (Note: Metal Bellows Corporation has built a limited number of units with outside diameters as small as 0.112 in.). However, for initial tests, a nickel corrugated-type bellows was used because it was readily attainable at a reasonable cost.

TABLE II. Design Data for 1/8-in.-diam Bellows System

Bellows[a]	
Convolutions	Corrugated
Material	Nickel (sulfur-free)
Inside diameter	0.075 in.
Outside diameter	0.125 in.
Free length	0.30 in.
Effective area	0.0078 in.^{2}
Spring rate	5.14 lb/in.
Pressure Transducer	
Type	CEC 4-317 strain gauge
Pressure rating	150 psig
Temperature rating	600°F
Effective diaphragm diameter	0.5 in.
Deflection at rated pressure	0.0008 in.
Capillary Tube	
Material	Type 304 SS
Length	25 ft
Inside diameter	0.012 in.
Outside diameter	0.063 in.

[a]Product of Servometer Corp., Clifton, N. J.

1. System Assembly

With reference to Fig. 15, the sequence of system assembly was as follows:

a. Clean the capillary tube with successive 4-oz rinses of acetone, ethyl alcohol, and a pickling agent (12.5% HNO_3-2.5% HF-85% H_2O). Flush with ethyl alcohol and dry with argon.

b. Beam-weld one end of the capillary tube to the upstream end fitting of the bellows. Similarly weld the short length (6 in.) of the

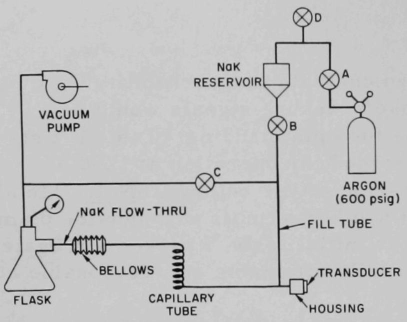

Fig. 15. Schematic of Test Assembly of 1/8-in.-diam Bellows System

NaK flowthrough tube to the downstream end fitting of the bellows. (Note: It was observed later that the flowthrough tube should have a small ID/OD ratio to ensure a sound pinch-seal upon completion of the NaK-filling operation.)

c. Clean the welded assembly as described in step a.

d. Heli-arc weld the transducer with the diaphragm exposed to the interior of the housing (1.125-in. OD, 1 in. long). Similarly weld the fill tube (1/8-in. OD, 1/16-in. ID) leading from the NaK reservoir to the transducer housing. (Note: Great care was exercised to prevent weld cavities. For example, all weld joints were tight and designed so that the weld penetration gave a smooth interior surface. Parts to be welded and the transducer diaphragm were pickled, as in step a, rinsed with ethyl alcohol, and dried with argon.)

e. Beam-weld the capillary tube to the transducer assembly to complete the system.

Preparations were then made to fill the system with NaK. To conserve space, the capillary tube was rolled into a 1-ft-diam coil. Three thermocouples were equally spaced around the periphery of the coil, and a heating tape was wrapped around the tube. Thermocouples were attached to the bellows and the transducer, and both components were wrapped with a single heater tape. Finally, the coil, bellows, and transducer were covered with insulation.

2. NaK-filling Procedure

Several filling procedures were carried out before essentially full deflection was observed on the potentiometer. With reference to Fig. 15, the procedure in this case was as follows:

a. Plumb the system. Open valve C; close valves A and B.

b. Start the vacuum pump; energize the heater tapes. Heat and evacuate the system until the vacuum gauge on the flask reads less than 1 μ. (Note: Average temperatures were: transducer, 475°F, capillary tube, 750 ± 50°F; bellows, 630°F.)

c. Close valve C, and open valves A and B. Pressurize the NaK reservoir and backfill the system slowly until NaK droplets are observed in the flask.

d. Close valve B. Allow NaK to remain in the system at the preset temperature for 4 hr. Open valve B, and continue backfilling until 4 oz of NaK (system volume) are observed in the flask.

e. Pinch the NaK flowthrough tube. Deenergize the heaters. Close valve A; open and close valve D to vent the NaK reservoir.

f. Cool the system to room temperature. Close valve B, and pinch the fill tube.

g. Sever, clean, and seal-weld the pinched end of the flow-through and fill tubes.

At this time, a slight compression stroke of the bellows resulted in a transducer diaphragm deflection equivalent to 15 mV, indicative of a voidless fill. With previous fills, there was no evidence of deflection, even when the bellows was compressed to its full stroke.

Attempts to calibrate the system were terminated because of bellows failure in an area adjoining the capillary tube. The failure was attributed to embrittlement of the nickel during welding.

IV. CONCLUSIONS

Although limited in scope, the foregoing out-of-pile tests on both systems were successful to the extent that the principle of operation merits further research and development effort. With improvements in filling operations and techniques, a commercially available stainless steel bellows of 0.220 in. OD used in conjunction with a capillary tube of 0.012 in. ID would satisfy the criteria established for LMFBR fission-gas pressure sensors.

ACKNOWLEDGMENT

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